Vertical atmospheric flow on Titan as measured by the HASI instrument on board the Huygens probe

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[1] On January 14, 2005, the Huygens probe descended on the surface of Titan, the largest moon of Saturn and the only moon in the Solar system with a substantial atmosphere. After the deployment of the main parachute and the release of the heat shield at an altitude of about 150 km, the local pressure and temperature were measured by HASI (Huygens Atmospheric Structure Instrument) all the way down to the surface. These measurements have now been used to determine the vertical component of the atmospheric flow along the trajectory of the probe. The average flow direction is rising below about 40 km and sinking above that, with features that loosely match the strong shears in the horizontal wind profile obtained by radio telemetry. The prevalence of sinking motion in the stratosphere is an unexpected result for the given latitude, suggesting a layered atmosphere with a large thermally indirect cell. Wiggles superposed on the main upward flow are evidence of inertial instability characteristic of equatorial regions, pointing to a latitudinal shear of zonal wind throughout the lower atmosphere. **Citation:** Mäkinen, J. T. T., A.-M. Harri, T. Tokano, H. Savijärvi, T. Siili, and F. Ferri (2006), Vertical atmospheric flow on Titan as measured by the HASI instrument on board the Huygens probe, *Geophys. Res. Lett.*, *33*, L21803, doi:10.1029/2006GL026982.

1. Introduction

[2] Titan, the largest moon of Saturn is the only moon in the Solar system having a substantial atmosphere. The thick atmosphere is completely opaque and featureless in visible wavelengths because of the prevalent aerosol haze whose formation and transport is coupled with atmospheric dynamics [*Rannou et al.*, 2002]. Before the Cassini-Huygens mission our main sources of information about the dynamics came from Voyager flybys [*Tyler et al.*, 1981] and telescopic infrared and stellar occultation observations. Combined with Titan-specific general circulation models (GCMs) they suggested that the atmosphere was in a state of superrotational cyclostrophic circulation like the one on Venus, with meridional and vertical winds that are weak in comparison with the zonal winds, but unlike Venus with strong seasonal effects [*Flasar et al.*, 1981].

[3] The Huygens probe descended through the atmosphere of Titan on January 14, 2005, and provided an excellent set of observations in the atmosphere and on the surface of Titan [*Lebreton et al.*, 2005]. During the 2.5-hour descent the HASI instrument package [*Fulchignoni et al.*, 2002] observed a comprehensive set of variables, including pressure, temperature, density and atmospheric electricity [*Fulchignoni et al.*, 2005]. The atmospheric pressure profile was measured by the Pressure Profile Instrument (PPI) provided by FMI [*Harri et al.*, 1998; *Mäkinen et al.*, 1998], and temperature with the temperature sensor (TEM) provided by CISAS [*Ruffino et al.*, 1996]. PPI and TEM started measurements after the heat shield had been discarded and the main parachute opened at an altitude of about 150 km and their operations continued well beyond the time of surface impact, at about 10°S and 192°W. The observations yielded the atmospheric pressure and temperature profiles depicted in Figures 4 and 5 of *Fulchignoni et al.* [2005], with a surface pressure of 1470 hPa and a temperature of 94 K, in agreement with estimates based on remote observations. Earlier ground-based and fly-by information suggested that the atmosphere of Titan consisted mostly of nitrogen with some fraction of methane and argon. The exact composition was measured by the GCMS instrument during the descent [*Niemann et al.*, 2005].

[4] Characteristics of the atmospheric circulation on Titan was to be monitored with the Doppler Wind Experiment (DWE) instrument [*Bird et al.*, 2002] consisting of two atomic rubidium oscillators, one on the Huygens probe and the other on the Cassini orbiter. DWE did not, however, achieve its objective in the intended way because of a misconfiguration in the receiver [*Lebreton et al.*, 2005]. Fortunately, the horizontal wind profile could later be reconstructed by ground-based radio telemetry [*Bird et al.*, 2005], confirming the existence of prograde superrotational zonal winds as had been predicted. But while the horizontal component of the atmospheric flow could be determined by tracking the motion of the probe during the descent, the much smaller vertical component could not be separated from the overall trajectory by such means. However, the HASI measurements provide an independent way of determining the vertical component.

2. Methods and Results

[5] The structure of the atmosphere above 150 km was determined from accelerometer measurements only [*Fulchignoni et al.*, 2005] but below that point very accurate pressure and temperature measurements became available.

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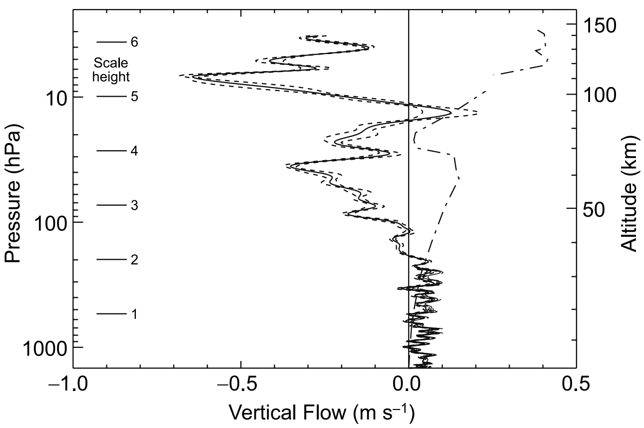

Figure 1. The vertical component of the atmospheric flow on Titan along the descent trajectory of the Huygens probe with error margins based on estimated instrument performance, and the horizontal component derived from radio telemetry [*Bird et al.*, 2005] scaled down by a factor of 1/250 for easier comparison (dash-dotted line). The general features are the rising area in the troposphere below 40 km and above that two sinking vortices separated by a through at around 90 km. The amplitude of the vertical flow is about 1% of the respective zonal wind and has a generally similar vertical profile except above 110 km where the vertical flow strongly decreases while the zonal wind increases.

These observations, combined with GCMS measurements of the composition of the atmosphere were used to reconstruct the altitude and descent velocity profile of the probe. The equation of motion of the descending probe can be written as

$$a = -g - \rho D v_d |v_d| \tag{1}$$

where a is the acceleration of the probe, g the effective local gravitational acceleration, ρ the atmospheric density, $D = SC_D/2\ M$ a drag factor combining reference area, drag coefficient and probe mass, and v_d the velocity of the probe relative to the local atmospheric flow, respectively. Thus $v_d = v - v_z$ where v is the vertical velocity of the probe and v_z the vertical wind velocity relative to the surface of Titan. Additionally, a real gas equation of state, the hydrostatic equation for the atmosphere, and the kinetic correction equation to obtain the ambient atmospheric pressure from the measured total pressure are needed to solve the descent profile [*Mäkinen*, 1996].

[6] For the first velocity profile reconstructions v_z was assumed to be zero [*Fulchignoni et al.*, 2005]. The value of the drag factor D depends on the configuration and attack angle of the probe and the local Mach and Reynolds numbers, and changed abruptly at an altitude of about 110 km when the main parachute was jettisoned and a smaller stabilizer chute was deployed. After a preliminary analysis of the data it was found out that the values of the drag factor D for the two probe-parachute combinations were not sufficiently constrained by pre-flight calibration, and therefore they had to be left as unknown quantities to be determined from the descent time observations. Since D is a very slowly changing quantity, it is possible to determine its value accurately from the data because each observation in the time series provides an independent set of equations, thus making the problem massively overdetermined.

[7] The case with zero vertical wind approximation could be solved pointwise, i.e., through normal integration methods. However, solving the full set of equations that way was not possible, especially with an unknown D. Instead, an optimization algorithm was used to determine v_z, parametrized with a dense spline curve. A standard optimization method, the modified Powell algorithm [*Press et al.*, 1986] was used to solve the governing equations with spline control points for v_z as free parameters and D a first order polynomial of its arguments, determined separately for the two configurations. Proper procedures like random initialization were observed to exclude methodological shortcomings. Error margins were estimated by inserting systematic bias and random noise to the data. Experimenting with different spline point densities suggested that an optimal value was about 80 control points distributed evenly in time over the descent. Less dense splines could not represent the fine details of the profile, and much denser ones failed to show additional detail but made the solution unstable. The optimal solution is depicted in Figure 1 with error margins derived from estimated instrument performance [*Fulchignoni et al.*, 2005]. Considering the low correlation coefficient (r = 0.17) between v_z and v, v_z appears to be separated from the much larger quantity to an acceptable degree. The value of D depended so little on its arguments that to a sufficient degree it was 0.074 m^2kg^{-1} for the main parachute configuration and 0.012 m^2kg^{-1} for the stabilizer chute configuration.

3. Discussion

[8] The main features in the vertical wind profile are perhaps the generally positive values (rising motion) in the troposphere below 40 km, the areas of negative values (sinking motion) with maxima at 70 and 110 km separated by a minimum at about 90 km, and short wavelength wiggles around the general pattern. The mass weighted average of the profile is close to zero in comparison to mass weighted average of the absolute flow velocity, a condition also observed in the atmosphere of the Earth. When compared with the respective horizontal wind profile [*Bird et al.*, 2005], it can be seen that the average behavior of the two profiles loosely correlates, the strength of the vertical wind being about one percent of the horizontal one. Both indicate very quiet winds in the lower troposphere, increasing with altitude up to about 60 km, then again from 80 to 110 km. Above 110 km the horizontal wind increases strongly while the vertical wind again decreases.

[9] Since the probe traversed a longitudinal distance of 166 km after the parachute deployment [*Bird et al.*, 2005] our data represent a slightly tilted vertical cross-section, so the likelihood that the probe crossed different cells cannot be totally dismissed. However, the meridional circulation can generally be expected to be more longitudinally uniform than latitudinally. Therefore, our data provide an important constraint on the vertical structure of the meridional circulation pattern in the equatorial region of Titan, while it is not possible to retrieve the lateral extent of the meridional cell.

[10] The meridional circulation of Titan is largely unknown from observations although the seasonal change in

Titan's brightness is evidence of meridional transport of aerosols and reversal of the meridional flow around the equinox [*Lorenz et al.*, 2004]. Virtually all Titan GCMs predict the presence of a thermally direct either pole-to-pole or equator-to-pole Hadley cell extending from the surface with upwelling at low southern latitudes in the season of Huygens entry [*Hourdin et al.*, 1995; *Tokano et al.*, 1999, 2001; *Rannou et al.*, 2002, 2006; *Hourdin et al.*, 2004; *Grieger et al.*, 2004]. Therefore, the measured upward flow in the troposphere is likely to be part of the tropospheric thermally direct cell. However, the remarkable reversal of the vertical wind direction near the tropopause is not consistent with the further extension of this cell up to the stratosphere. Instead it indicates that the meridional circulation pattern changes sign across 40 km. Since the downward flow extends over a vertical distance of at least 100 km this gross behavior is unlikely to be a transient feature and it points the presence of a thermally indirect cell. Such a cell is consistent with the high static stability of the lower stratosphere of Titan.

[11] Several GCMs predict the existence of a small equatorial streamline vortex centered near 90 km [*Hourdin et al.*, 1995; *Luz et al.*, 2003; *Rannou et al.*, 2006]. This matches nicely with the minimum in our vertical velocity at 90 km at 10°S. The sinking motion branches of this vortex (above and below 90 km) were however at about 10°N in the work of *Hourdin et al.* [1995] at $L_S = 270°$. Our vertical velocity profile therefore suggests the existence of a thermally indirect cell in the stratosphere with an opposite circulation sense as in the troposphere [*Tokano et al.*, 1999]. This cell would be sandwiched between two thermally direct cells in high static stability of the lower stratosphere, and is dynamically forced. Such vertical layering of meridional circulation was suggested to exist in the atmosphere of Venus as well [*Schubert*, 1983].

[12] The sinking motion above 40 km indicated by our analysis differs from predictions made by GCMs, which suggest a consistently rising motion at 10°S in the season of Huygens descent. Our data indicate that the thermally indirect cell seems to have a much larger vertical extent than previously thought. This may indicate that the deposition of radiation in the lower stratosphere is probably not properly represented in previous GCMs. The fact that our analysis is based on accurate *in situ* observations gives credit to the reconstructed profile. Our profile also meets the zero mass weighted average condition without it having been forced into the solution, which increases confidence in the results of our analysis.

[13] The wiggles seen in the vertical profile indicate the presence of a transient feature superposed on the basic upward and downward flow. Saturn's gravitational tide is not expected to cause oscillations in excess of cm s^{-1} in the lower atmosphere [*Tokano and Neubauer*, 2002; *Strobel*, 2006]. Gravity waves forced near the surface could generate vertical amplitudes similar to those observed [*Friedson*, 1994]. However, the amplitude of upward propagating gravity waves would grow with altitude with $\rho^{-0.5}$, while our data show that the amplitude is nearly constant within the troposphere. Therefore, gravity waves alone seem to be insufficient to explain the wiggles. On the other hand, inertial instability is known to cause such oscillation in the equatorial region [e.g., *Fortuin et al.*, 2003] and is predicted to exist in Titan's lower atmosphere [*Luz et al.*, 2003]. The GCM of *Luz et al.* [2003] indicates eight of these cells below 40 km, which is compatible with the observed wiggles. Inertial instability is a parcel instability characteristic of the equatorial atmosphere caused by the latitudinal shear of zonal wind and occurs when the potential vorticity changes sign. Within the inertial instability mass overturning through numerous vertically stacked meridional circulation sub-cells takes place, manifesting themselves, e.g., in wiggles in the vertical profile of meridional and vertical wind.

[14] If the inertial instability is responsible for the observed oscillation in the vertical flow, it would also produce similar oscillation in the meridional flow with amplitudes about one order of magnitude larger than for vertical flow, i.e., of the order of m s^{-1}. The deviation from the fitted curve of the observed image points of the probe during the descent [*Tomasko et al.*, 2005] may be evidence of such meridional oscillation. Unlike gravity waves the amplitude of the oscillation associated with inertial instability would be given by the strength of the horizontal wind shear, thus indicating that the shear may exist throughout the troposphere. A Fourier analysis of the lower part of the vertical velocity profile did not indicate enhanced activity at any specific frequency, including the local Brunt-Vaisala frequency. This seems to agree with Cassini radar observations which indicate that the surface of Titan is very flat without any major topographical features [*Elachi et al.*, 2005] and thus there is little orographic forcing of gravity waves in the atmosphere. The vertical stacking of meridional circulation on Titan would have an important consequence for the generation mechanism of stratospheric superrotation. Upward transport of angular momentum at low latitudes by the Hadley circulation as proposed in the Gierasch mechanism [*Gierasch*, 1975] would be severely hampered.

[15] The downward flow above 100 km should cause adiabatic heating that by far exceeds the expected radiative heating. The adiabatic heating rate is $-(g/c_p)v_z$, which is of the order of 10^{-4} K s^{-1}. The net radiative heating rate in this season is merely of the order of 10^{-7} K s^{-1} [*Tokano et al.*, 1999]. The Cassini CIRS (Composite InfraRed Spectrometer) unexpectedly found out that the stratosphere is warmer around the equator than at the south (summer) pole [*Flasar et al.*, 2005]. Given our wind data and inability of previous GCMs to correctly reproduce the stratospheric temperature profile, the adiabatic heating may by far dominate the radiative one, and may explain the warm equator seen by Cassini. On the other hand, the upward wind in the troposphere is not as strong as inferred from the temporal variation of mid-latitude clouds [*Griffith et al.*, 2005] or predicted in convective clouds [*Tokano et al.*, 2001]. This is the most direct proof that Huygens did not encounter convective updrafts, in agreement with the non-detection of convective clouds during the descent [*de Pater et al.*, 2006].

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